New Software for Measurements of the Anisotropic Resistivity by Multiterminal Technique

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We present an overview of the capabilities of a new software developed for use with multiterminal measurements. The program supports two configurations of current and voltage contacts known in the parlance of the field as "flux transformer" and " I$\|$c" geometries. The problem of instability of the results obtained by the multiterminal method and the ways to overcome it is also discussed.

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I. INTRODUCTION

Even today, the most commonly used method of measuring resistivity is a four-point method in which a uniform distribution of current is created along a certain direction in a sample of a given cross-section. This allows to determine one component of the resistivity tensor. The multiterminal method, in contrast, is based on creating a strongly nonuniform two-dimensional distribution of current in a sample of a given geometry and measuring the voltage drops between the two pairs of voltage contacts attached to the surface in different places. Using the mathematical model of the current distribution, one calculates then the two components of the resistivity tensor from the measured voltages.

The advantages of the multiterminal technique are obvious. One needs only one sample, instead of two, in order to measure two components of the resistivity of an anisotropic medium. This alone reduces the time and expense of an experiment in half. Moreover, in many practically important cases the four-point method is difficult to apply due to specific shape and small size of available samples. This has been the case with the crystals of high critical temperature (high-T_c) superconductors, manganites exhibiting colossal magnetoresistance (CMR) and the number of other layered crystals available mostly in the form of very thin platelets. This makes it difficult to measure the resistivity component in the direction of the smallest dimension.

Perhaps even more important is that in some of the most interesting materials it is necessary to measure both components of the resistivity tensor on the same sample. Even the crystals from the same batch may have somewhat different concentration of dopants or/and impurities. If the resistivity strongly changes with elemental composition, one cannot reliably compare the temperature or magnetic field dependence of the two components of the resistivity tensor if they are measured on different samples.

Yet, the acceptance of the multiterminal technique for measurements of the *normal state resistivities* has been slow even for research purposes, not to mention the engineering applications. Friedmann et al. [2] have used a modified Montgomery method to measure the components of the resistivity tensor in untwinned single crystals of $YBa_2Cu_3O_{7-\delta}$. Later, Ando et al. [3] adopted an algorithm of Busch et al. [4] to obtain the two components of the normal state resistivity (ρ_c and ρ_{ab}) of $Bi_2Sr_2CuO_y$ crystals in high magnetic field.

A systematic approach to the development of the mathematical models describing two configurations of the current and voltage contacts, known in the parlance of the field as "flux transformer" and "I$\|$c" geometries, is described in Refs. [5–7]. The numerical algorithms based on these models were used to measure the resistivities of $PrBa_2Cu_3O_{7-\delta}$ [8], underdoped $YBa_2Cu_3O_{7-\delta}$ [9], and electron-doped $Nd_{2-x}Ce_xCuO_{4-y}$ [10]. Two other research groups later have developed similar programs. At Argonne the resistivities of CMR manganites have been measured by the multiterminal method [11,12], and an ISTEC group have investigated the applicability of the multiterminal technique to the mixed state of superconductors [13].

Apparently, the main obstacle to a wider acceptance of the multiterminal method has been a relative complexity of the calculations involved in determining the values of the resistivities from the measured voltages. Here we present a brief outline of a new software developed specifically for that purpose. One of the main goals of this project has been to facilitate the implementation of the multiterminal technique in common practice by allowing other research groups to avoid wasteful and costly duplication of the development of the mathematical models, programming and testing so characteristic of the current situation.

II. SOFTWARE CHARACTERISTICS.

The software package called *Ariadne* is available for download from the website **www.virtinst.com**. The algorithm by which this program calculates the components of the resistivity tensor is based on the method of Refs. [6,7]. However, the capabilities of our software are

significantly enhanced by inclusion in the mathematical models of the flux transformer and I||c configurations the options of an arbitrary offset of the current contacts from the edge of the sample and an arbitrary width of the current and voltage contacts. This makes the models much more realistic and allows to carry out a very important test of the stability of the results with respect to variations of the input parameters.

The algorithms are thoroughly optimized. Even when the current contacts are offset from the edges of the sample and have a finite width, it is possible to eliminate unnecessary summation of the slowly convergent series. As the result, it takes Ariadne a fraction of a second to find a solution on a regular PC with the accuracy of 10^{-7} or better (needless to say that such an accuracy is excessive given a much greater error with which the geometrical parameters of the sample are typically measured). In our tests the large data files with hundred entries have been processed in a few seconds.

Other features include:

• The ability to run batch jobs, i.e. to process several input data files in a row without user interaction.
• Multithreaded processing, so that a user has complete access to the user interface even while a job is being run.
• Control over how the input files are formatted, output files are created and named, and what goes into them.
• Comprehensive error reporting mechanism to ensure reliability of the calculations.
• Clean and intuitive interface.
• Context-sensitive help.

III. STABILITY OF THE RESULTS.

In the four-point method an error in determining the exact distance between the voltage contacts results in equivalent relative error in the value of resistivity. The situation is more complex with multiterminal measurements. In certain cases a relatively small variations of the input parameteres result in much greater relative variations of at least one of the components of the resistivity tensor.

One example of such "instability" is when the flux transformer configuration is used to determine the resistivities of a sample which is either too thin or not anisotropic enough, so that the distribution of the density of current is close to uniform. The "vertical" component of the current density is small in comparison with the "horisontal" one and therefore the relative error in determining the respective component of the resistivity (ρ_c) is necessarily substantially greater than that for ρ_{ab}. However, such instability has subtle manifestations and may remain undetected. Any software calculates the resistivities from the measured voltages with a preset accuracy. This, however, does not mean that the resistivities are indeed determined with that accuracy. To detect the low stability of the metod one has to calculate the resistivities from the same voltages using slightly different values of the geometrical parameters, especially those that are determined least precisely. In our example one would find that the calculated values of ρ_{ab} change very little with the small variations of the width of the contacts and the value of their offset from the edges of the samples. In contrast, the calculated values of ρ_c vary much more strongly in response to the variations of these input parameters.

The solution of such a problem is to use either the alternative configuration (I$\|c$) or a combination of both, and to take as the final results the values of ρ_c and ρ_{ab} that show the greatest stability with respect to error in determination of the geometrical parameters. Fast software like Ariadne which also allows to run batch jobs makes this tedious work much easier.

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